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Simulation on the distribution of solid ice and prediction of ice blockage for ice slurry in horizontal straight tubes

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Abstract

Ice slurry has been widely used as a second refrigerant for its high energy density and pumpability in HVAC systems and other district cooling areas. However, the ice blockage becomes a serious problem for the application of ice slurry, which makes the thermal storage technology unavailable in many cases. In this paper, the distribution of the ice crystals is analyzed in the straight tubes to predict and avoid ice blockage based on numerical simulation by kinetic theory of granular. Additionally, it is proposed in this paper that two index parameters, the maximum concentration (namely, the volume fraction, so as the following ones) and the minimum concentration of ice particles, are proved useful to evaluate the risk of the ice blockage, not previously considered. Three distinguished flow patterns has been observed keeping accordance with previous research. The most remarkable conclusion is that optimum flow velocity exists just between these two critical velocities to prevent ice blockage to the most degree.

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*Keywords:*Ice blockage; Numerical simulation; Distribution of ice particles; Maximum ice concentration; Critical velocities

1. Introduction

The ice slurry, a kind of cool agent, has shown great advantages for high cooling capacity, good flow characteristics and pumpability, compared with the conventional technologies, such as ice-thermal storage technology [1]. It is made up of ice crystals, water and certain depressant additives. Hence, large latent heat is

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absorbed by ice slurry due to the presence of ice crystals, which permits that the heat exchanger could be designed more compact.

Nomenclature

V volume	$\vec{v}_{pq}$ relative velocity between phases
α volume fraction of one phase	$\vec{F}_{lift}$ lift power
$\hat{\rho}$ effective density	$V_{i,total}$ total volume of ice in the tubes
ρ physical density	$V_{w,total}$ total volume of water in the tubes
$\vec{v}$ velocity	c average volume concentration of solid ice within corresponding color zone
$\dot{m}_{pq}$ mass transfer from phase p to phase q	v_p volume of each color zone
p mutual force applying on the all phases	
$\bar{\bar{\tau}}$ stress-strain tensor	*Subscript*
$\vec{F}$ external body force	p either of the two phase
$\vec{F}_{Vm}$ virtual mass force	q the other phase

In recent years, the ice slurry has been increasingly used in practical applications, such as the HVAC systems (Heating Ventilation Air Conditioning), the food cooling area, the medical and health systems and the shipping industry, etc. [2]. Compared to other countries, Japan probably has the largest number of installed ice slurry systems [3]. A schematic depicting ice slurry coolant was made in a central plant and delivered by pipes to multiple distributed site cooling loads [4].

Many scholars have researched on the ice slurry [5,6,7,8,9]. Ashley C.S [10] reviewed four rheological models, namely Bingham, Casson, Power and HerscheleBulkley, which can predict the behavior of ice slurry in tubes on specific conditions. Doron[11,12] proposed three kinds of flow patterns to describe the ice slurry flow: stationary-bed, moving-bed and suspension-bed flow. It was applied by Liu Yonghong[13] to develop new expressions fit for suspension bed. Qiqi Tian found out the effects of the particle size, the IPF(Ice packing fraction), the additive concentration and the pipe size on transportation safety by numerical simulation based on the flow pattern transition[18]. Wang Jihong [14,15] made numerical investigation on ice slurry flowing through the horizontal 90ºelbow and found a clear secondary flow phenomenon which enhances the mixing between ice particles and carrier fluid. De-Pan Shi [16] developed a Euler-Euler two-fluid model incorporating the kinetic theory of granular flow to describe the steady-state two-phase flow in a tubular loop propylene polymerization reactor composing of loop and axial flow pump. Ming Gang [17] found that flow resistance of ice slurry in the horizontal tubes increases firstly, then goes down when the IPF increases.

Practically, the ice blockage is a serious problem [18] for the application of the ice slurry which not only causes the block of pipes, but also worsens the heat transfer between tubes and environment. This problem is resulted from the high density of ice particles and the low ambient temperature. In order to solve this problem, it is necessary to determine the distribution of the solid ice particles which is invisible and hard to measure by experiments. The aim of this study is to make analyses on the distribution of the ice crystals in the straight tubes to predict and avoid ice blockage, by numerical simulation based on kinetic theory of granular. The numerical results are verified by, and compared with, experimental data measured by γ-ray densitometer of high accuracy and also high expense.

2. Theoretical model analyses

The simulation of the ice slurry is carried out based on the kinetic theory of granular dynamics. Energy option is selected and gravity is considered. In addition, RNG mixture option under k- model is selected to describe the turbulent flow.

2.1. Conservation of mass

Euler-Euler model was used to describe the flow of the multiphase fluid. Function of volume fraction are calculated by following equation:

The volume of phase q:

$$V_q = \int_V \alpha_q dV \tag{1}$$

$$\sum_{q=1}^{n} \alpha_q = 1 \tag{2}$$

The effective density of phase q is calculated by Eq(3)

$$\hat{\rho}_q = \alpha_q \rho_q \tag{3}$$

The continuity equation for phase q is shown as:

$$\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \overrightarrow{v_q}) = \sum_{p=1}^{n} \dot{m}_{pq} \tag{4}$$

2.2. Conservation of momentum

The ice slurry is regarded as two-phase liquid containing particles which show granularity, so that the momentum equation of liquid phase is shown as[19]:

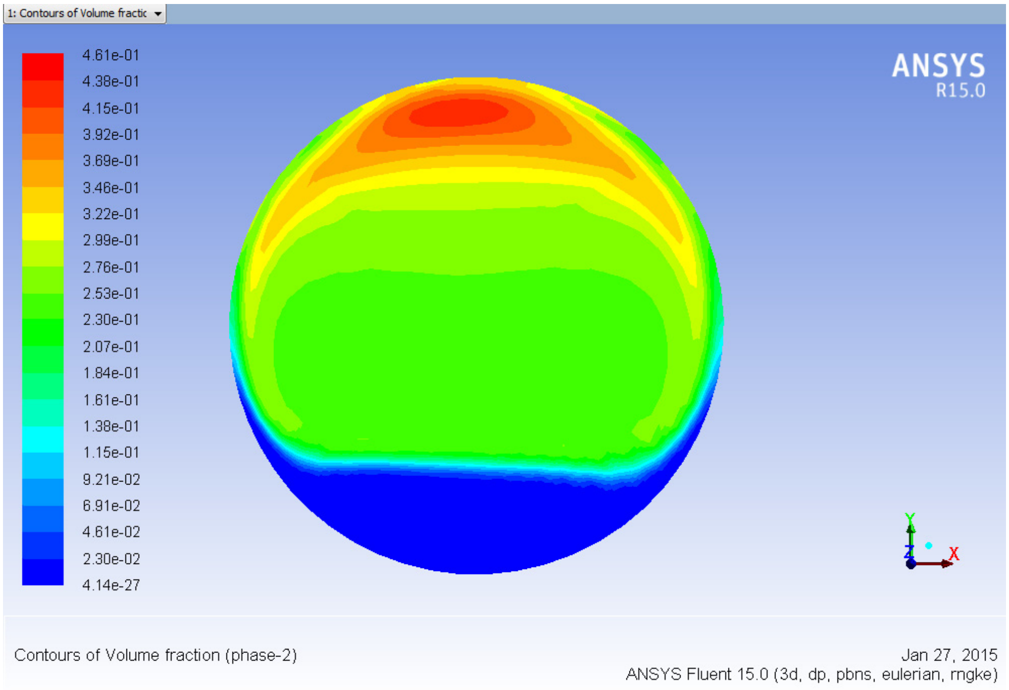
$$\begin{aligned}\frac{\partial}{\partial t}\left(\alpha_q \rho_q \vec{v}_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{v}_q \vec{v}_q\right) &= -\alpha_q \nabla p + \nabla \cdot \overline{\overline{\tau}}_q + \alpha_q \rho_q \vec{g} \\ &+ \alpha_q \rho_q (\vec{F}_q + \vec{F}_{lift,q} + \vec{F}_{Vm,q}) + \sum_{p=1}^{n} \left(K_{pq}(\vec{v}_p - \vec{v}_q) + \dot{m}_{pq} \vec{v}_{pq}\right)\end{aligned} \tag{5}$$

3. Results and discussions

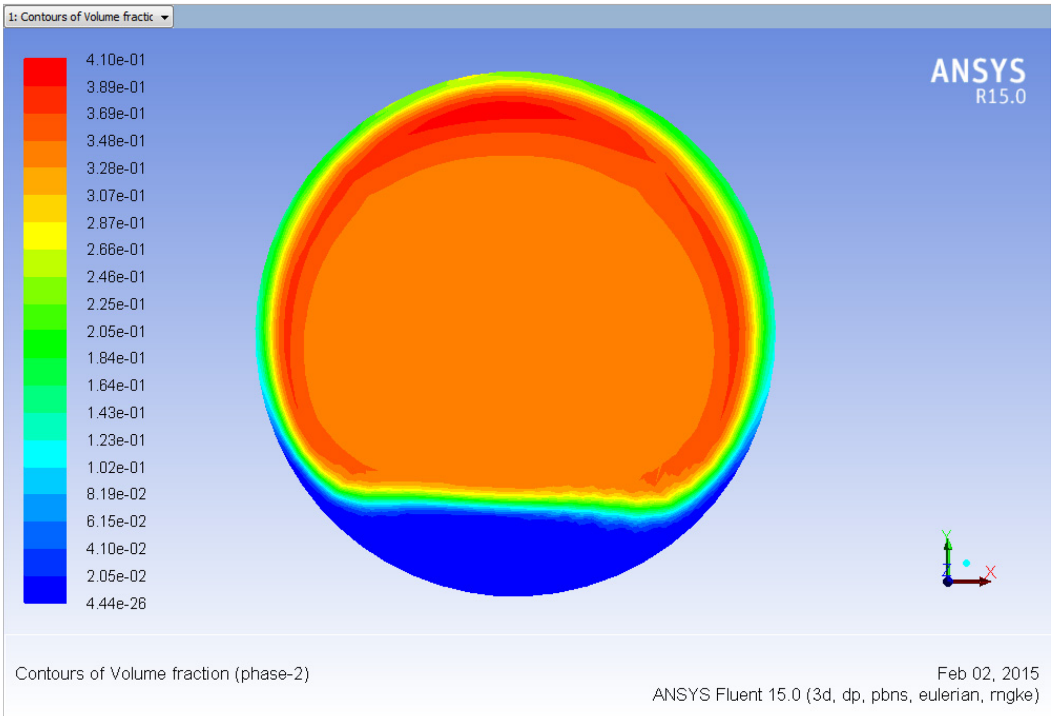
3.1. The distribution of ice particles

The ice slurry for numerical simulation is made from liquid sodium-chloride solution and ice crystals are of diameters around 10-4 m. The diameter of the straight tubes is set to 0.02 m. For boundary conditions, the inlet is set as velocity type and the outlet is set as the outflow type. The flow condition is studied with changing the flow rates from 0.2m/s to 50m/s and IPF from 5% to 25%, on which condition the ice slurry can be regarded as non-Newtonian fluid[20]. The results of numerical simulationare shown in figures as follows.

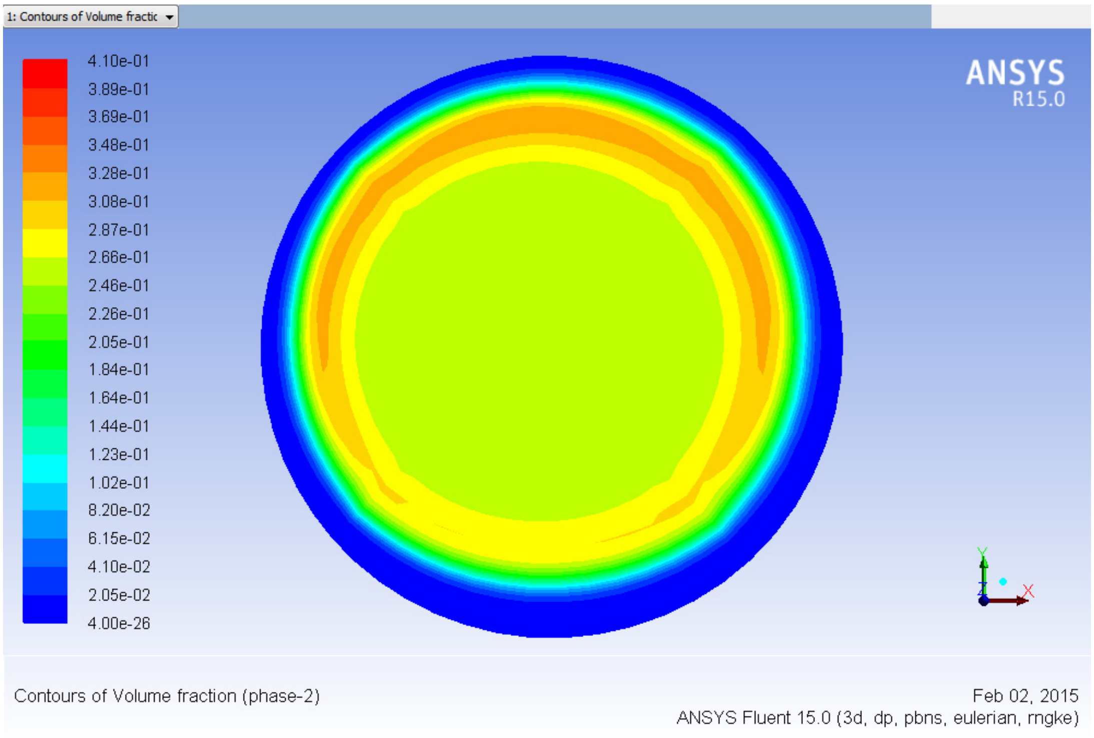
The contours of the volume fractiondistribution obtained by numerical simulation are used to indicate different conditions at variable velocities, as Fig.1(a)-(e)show. Several researches have been carried out to determine the distribution of the ice and the flow patterns, which can be found that the simulation results show a good agreement with previous data and description present in the previous published researches. It is found by Doron[12] that the ice slurry can be presented as three evident flow patterns by the increasing flow velocity, i.e. the stationary bed, the moving bed and the suspension bed, as shown in Fig.2(a)-(c). This theoretical model was applied by Liu Yonghongand she developed new expressions fit for suspension bed. Qiqi Tian[18]made analyses on the transportation safety by simulating the flow patterns of ice slurry in tubes. The stationarybed flow occurs at a much lower flow rate in which condition the carrier fluid is unable to carry part of the moving-bed layer at the top of the movingbed layer, leading to the forming of the stationary-bed layer at the top of the tube. The movingbed flow occurs at a higher velocity than the former pattern with stratified flow layers, in which case the top of tubes is a movingbed layer while the bottom is a heterogeneous flow layer. With the flow speed increasing to a certain high value, the flow pattern become transforming to the suspension flow which is thought to be a troublefree operating condition. It can beconcluded that transportation keep safety when the velocity exceed critical value,around which the flow patterns is transforming from the moving-bed flow to the suspension flow.



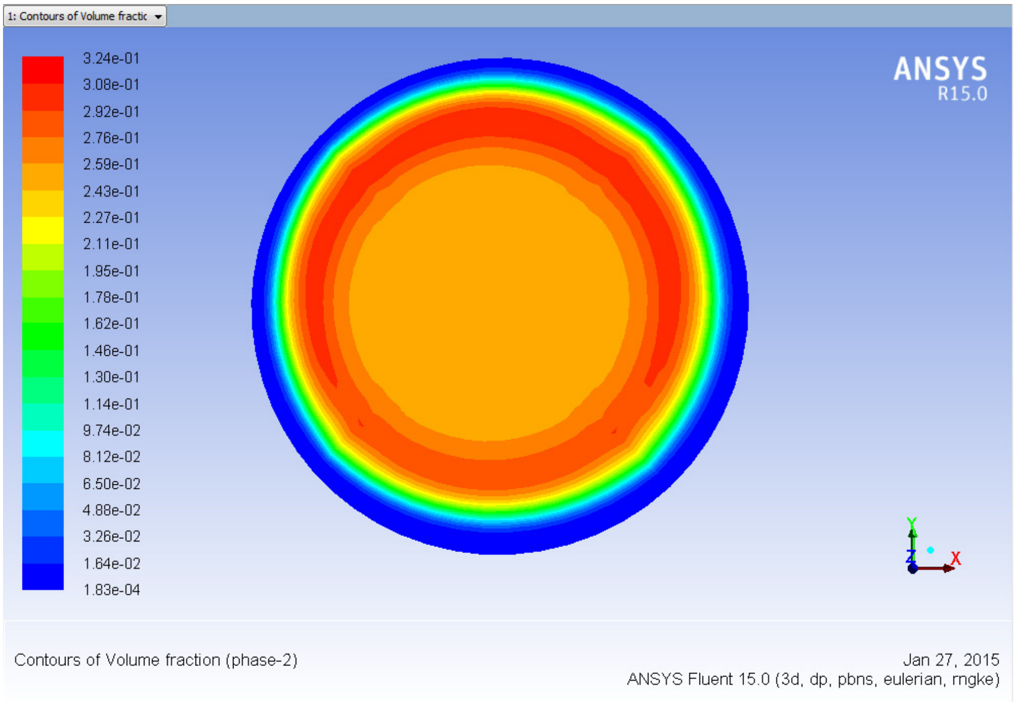
(a) v (flow velocity)=0.2m/s



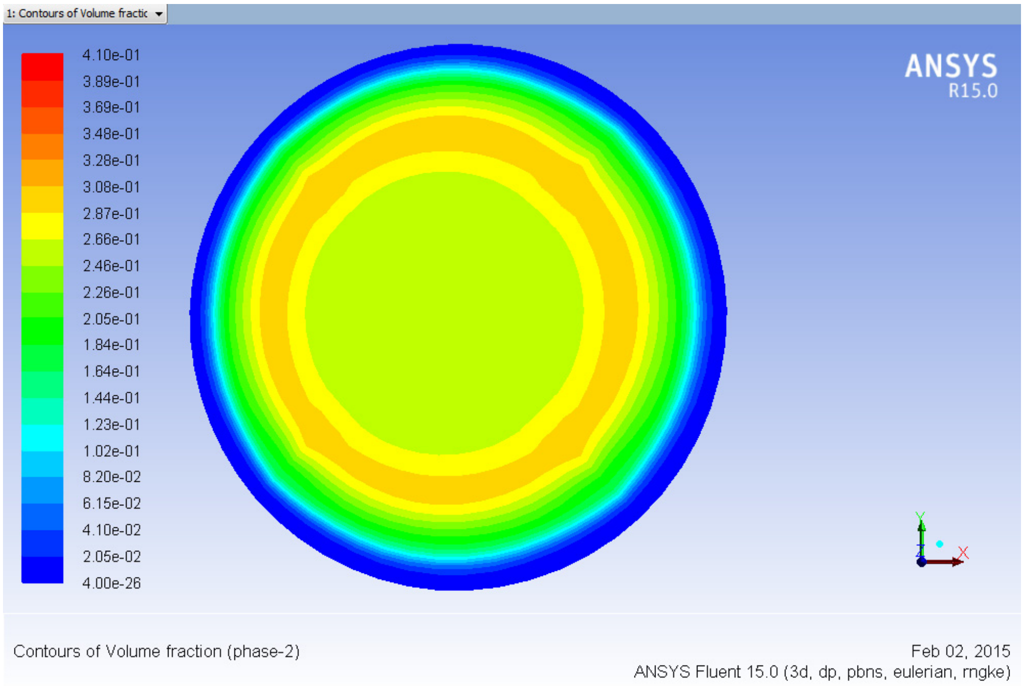
(b) v=0.3m/s



(c) v=1m/s

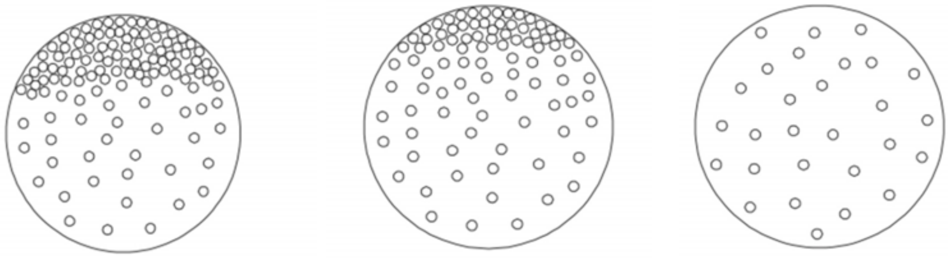


(d) v=1.5m/s



(e) v=3m/s

Fig. 1. The distribution of the solid ice in the cross section of tubes at different velocities



(a) Stationary-bed flow (b) Moving-bed flow (c) Suspension flow

Fig. 2. Schematic of three flow patterns found in published literature (Tian et al 2014)

As the color represents the value of the concentration, it can be seen from Fig.1(a) that the concentration of the ice particles from the top to the bottom are respectively the highest values, the transition area and the lowest area(i.e. the stationary-bed, the moving-bed and the suspension-bed) when the ice slurry flows at an extremely low velocity. Similarly, Fig.2(a) shows the stationary flow pattern occurring at low flow rate in which case the carrier fluid is unable to carry part of the moving bed layer, leading to the forming of the agglomeration of the ice crystals on the top of the pipe. The highest concentration for stationary-bed layer increases the risk of the stratification and ice blockage during the transportation to the most degree.

With the flow velocity adding to 0.5m/s and 0.5m/s, the ice crystals distribute around the wall of inner pipe which indicates that the concentration of the solid ice become lower compared with the stationary-bed condition, as Fig.1(b,c) show. Corresponding to the simulation results, Fig.2(b) shows the movingbed flow occurring at a higher speed in which condition the top layer is moving-bed flow while the bottom layer is a heterogeneous flow, namely so-called suspension-bed. The same for the simulation results, that literature’s results show that the concentration of the bottom layer reaches lowest within the whole tube.

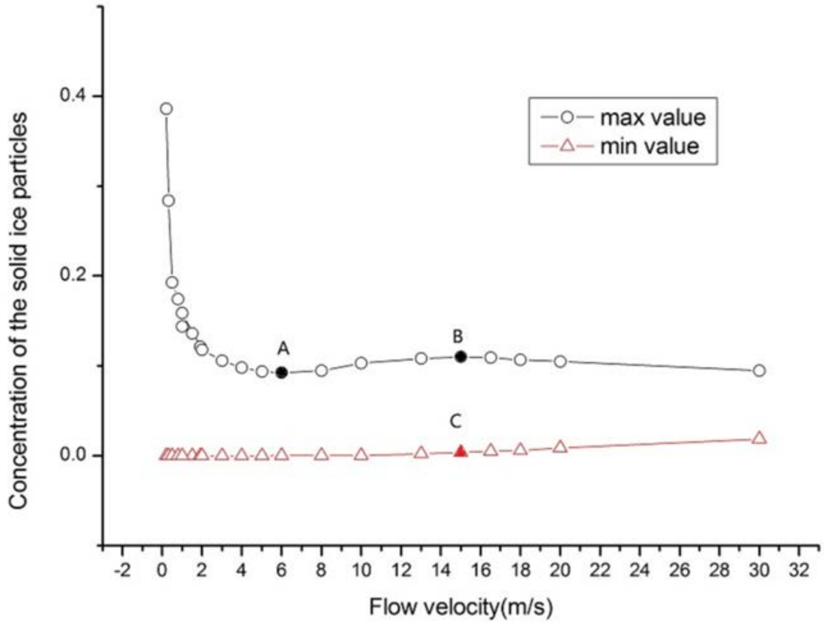
By making comparison of simulation results under different velocities ranging from 0.1m/s to 5m/s, 1.5m/s was selected as the second critical velocity when the slurry transforms from the moving-bed flow to suspensionbed flow. It can be seen from Fig.1(d,e) that all around the second ring (counted from the outer rings of the tubes to the inner rings) is similar with the third ring which indicates that the distribution of the solid ice tends to be most homogeneous.

3.2. Maximum and minimum value of the ice particles concentration

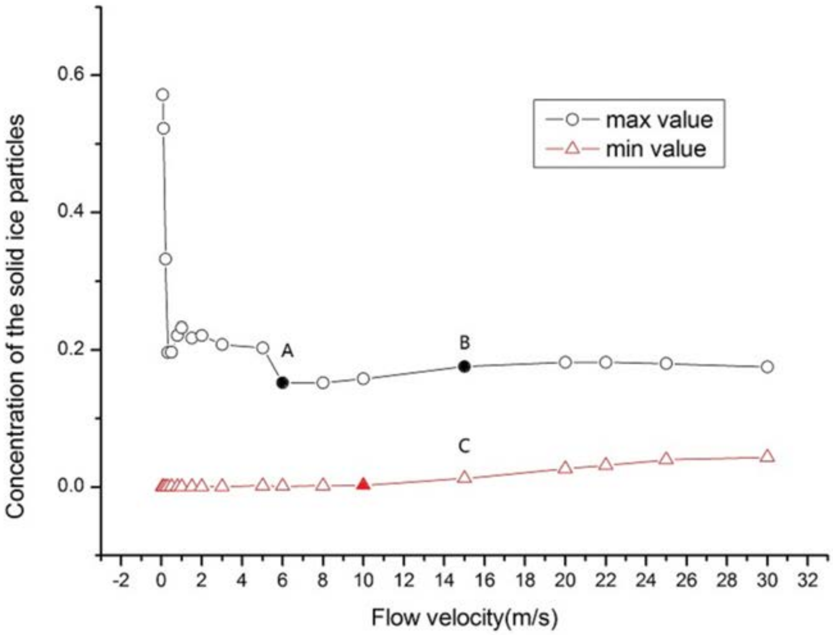
In this section, two parameters, the maximum and the minimum volume fraction of ice particles, which vary with different velocities are proposed to describe and to analyze the distribution of ice slurry under given IPF, as shown in Fig.3. It is observed that the variation trends of these two parameters under different flow rate show agreement with each other which make it possible to find out the solution to solve ice blockage. According to the contour of distribution of solid ice, the total volume of the ice slurry is given by:

$$V_{i,total} = \sum_{p=1}^{n} c \cdot v_p \tag{6}$$

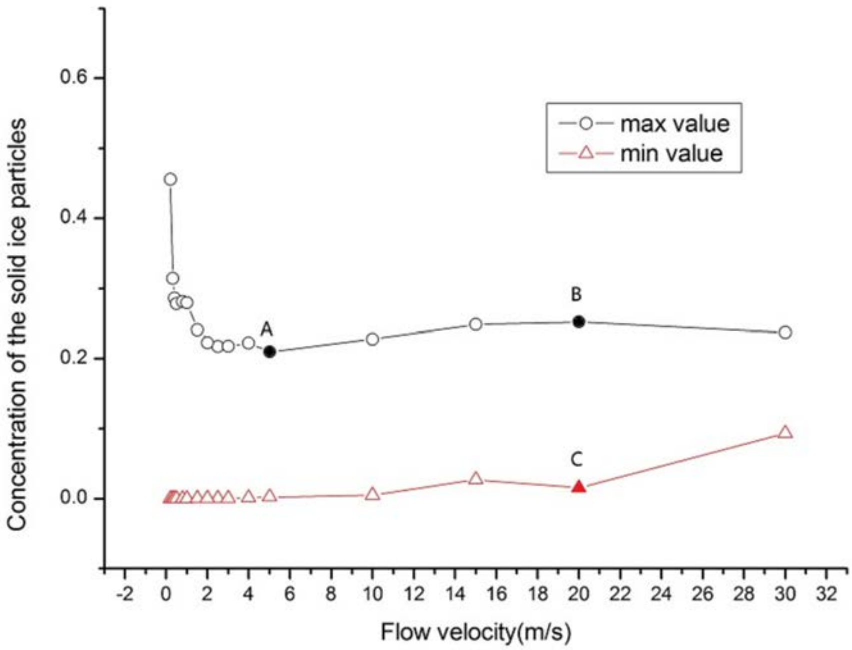
$$V_{w,total} = \sum_{p=1}^{n} (1-c) \cdot v_p \tag{7}$$



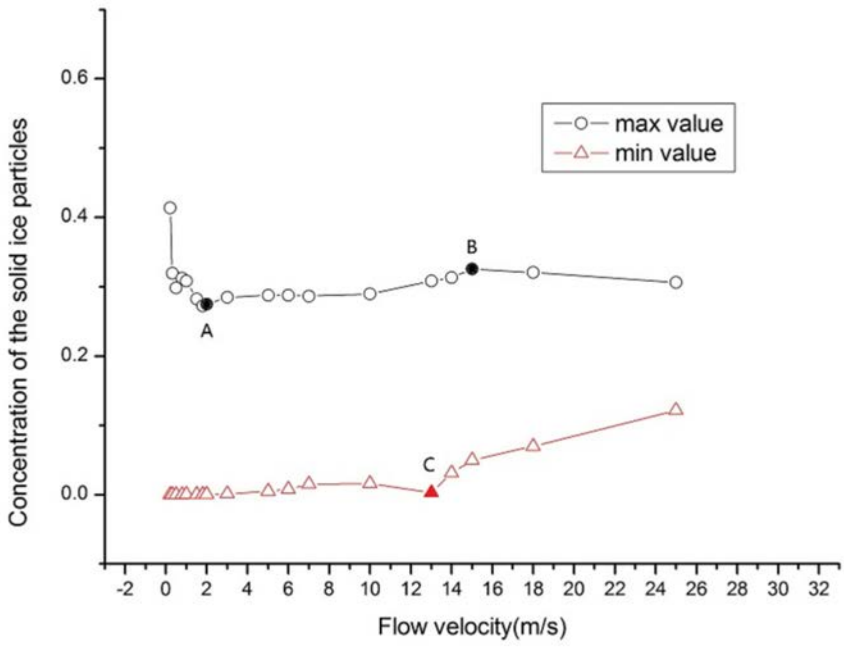
(a) IPF=5%



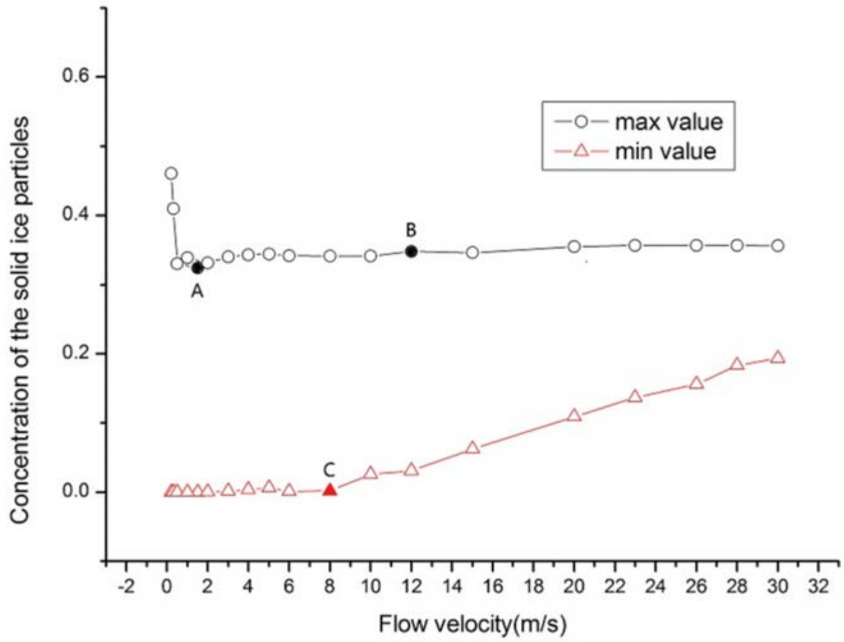
(b) IPF=10%



(c) IPF=15%



(d) IPF=20%



(e) IPF=25%

Fig 3. Variation of the maximum and minimum value of the ice particles concentration with velocity at different IPFs

It can be analyzed from Fig.3 that before the velocity reached point A, flow pattern is as Fig.1(a) shows, in above section, namely stationarybed on the top, moving-bed in the middle layer and suspensionbed at the bottom layer. With flow rate increasing up to point A, the so-called the first critical velocity, former stationary-bed layer generally transforms to the moving-bed flow as a ring distribution, as Fig.1(d) shows. After velocity reaches point C, called the second critical velocity, the maximum concentration drops down and the minimum value grows up rapidly, therefore, the final suspensionbed flow occurs.

The ice slurry is thought to be under viscous friction and disturbance due to the vortex and turbulent effects in tubes. First critical velocity indicates the change from stationary-bed to the moving-bed flow, which means that influence of turbulent effects are bigger than viscous friction. By comparing with Fig.3, it can be drawn that the first critical velocity, namely velocity of point A, becomes smaller with increasing IPF. The reason is that increasing IPF has a greater effect on the turbulent effects than on the viscous friction.

With increasing IPF, the velocity of point C decreases and has little difference with the corresponding velocity of point B. The second critical velocity indicates the variation from moving-bed flow to totally suspension-bed flow. This reduction for the second critical velocity can be explained by the same reason as first critical velocity. It can be concluded that ice slurry of higher IPF is more likely to transform to homogeneous flow at a lower velocity to reduce the risk of ice blockage.

Above all, it is available and reliable to study the distribution of solid ice in the tubes by numerical simulation, preventing the large error in the measurements. Besides, the whole variation trend of the distribution with varying velocity can be obtained without accounting for the limit of practical power supply at high velocity.

4. Conclusions

In this paper,it is analyzed that on the distribution of ice particles and flow patterns to predict and avoid ice blockage by using simulation based on the kinetic theory of granular dynamics. Maximum value and minimum value of concentration of solid ice particles are proposed to verify and explain the numerical simulation results. There are several conclusions drawn in this paper as follows.

It is available and reliable to study the distribution of ice particles and ice blockage in the tubes by numerical simulation, preventing the large error caused in the measurements. Simulation results show a good accordance with previous literature which verify the correct of the simulation model.

Three flow patterns were found to describe the flow behavior of the ice slurry by analyzing distribution of solid ice and most value of ice concentration. Stationary-bed flow occurs at extremely low velocity no more than the first critical velocity is of high risk in ice blockage. Moving-bed flow occurring at a higher rate is better than stationary-bed flow in preventing ice blockage, but not better than suspension-bed flow which occurs at highest velocity over the second critical velocity.

According to series of the most value curves, it can be seen that the first critical velocity and second critical velocity both decrease with increasing IPFs, which means that the influence of IPF on the turbulent effects is bigger than on the viscous friction.

The most remarkable thinking of this paper is the proposal of the maximum value and the minimum value, which makes the analyses quantitative and clear in the prevent of the ice blockage in the future study.

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